

# Variable Stars in the Archival HST Data of Globular Clusters M13, M30 and NGC 6712

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## ABSTRACT

We have analyzed archival *HST*/*WFPC2* time-series data of the central parts of globular clusters M13, M30 and NGC 6712 in search of variable objects. Among a total of 21 identified variables there are 15 new discoveries. The sample includes nine RR Lyr stars, two SX Phe stars and seven W UMa-type contact binaries. One object is preliminarily classified as a detached eclipsing binary and another as an ellipsoidal variable.

*globular clusters: individual: M13, M30, NGC 6712 – binaries: eclipsing – stars: variables: RR Lyr*

## 1 Introduction

The *Hubble Space Telescope* has an excellent resolving power and therefore offers an exceptional opportunity to explore the crowded central regions of Galactic globular clusters. The centers represent rich environments for the study of stellar evolution, dynamical processes in stellar systems as well as evolution of close binary systems.

Albrow *et al.* (2001) used HST/*WFPC2* time-series data to identify over one hundred variables in the central part of 47 Tuc. Pritzl *et al.* (2003) analyzed the archival data on NGC 6441 and located 57 variables, of which 38 were RR Lyr stars. Similarly, Pietrukowicz & Kaluzny (2003) used the archival *WFPC2* images to detect 8 new variables in the central region of globular cluster M22.

In this contribution we report identification of several new variable stars in fields covering nuclear regions of globular clusters M13, M30 and NGC 6712.

Table 1: Data sets

Name	Program	Date	Filter	Exposures
M13	GO 8278	1999 Nov 10	F555W	$25 \times 80$ s
		1999 Nov 10	F814W	$25 \times 140$ s
M30	GO 7379	1999 May 31–Jun 1	F336W	$8 \times 200$ s, $20 \times 300$ s, $10 \times 400$ s
		1999 May 31–Jun 1	F555W	
		1999 May 31–Jun 1	F814W	$32 \times 23$ s
NGC 6712	GO 6121	1999 May 31–Jun 1	F814W	$28 \times 30$ s
		1995 May 25–26	F300W	$8 \times 260$ s, $44 \times 300$ s, $1 \times 400$ s
		1995 May 28	F336W	
		1995 May 28	F439W	
		1995 May 28	F555W	
		1995 May 28	F675W	
		1995 May 28	F814W	160 s
				160 s
				60 s
				60 s
				120 s

## 2 Data Reductions and Results

Observational data consisting of processed WFPC2 images were obtained from the Multimission Archive at Space Telescope \*. A condensed log of observations used is given in Table 1.

Data reductions and analysis were performed using an approach which is described in more detail in Pietrukowicz & Kaluzny (2003). Profile photometry was extracted with the help of the HSTphot package (Dolphin 2000a; 2000b). The same package was used to transform instrumental photometry to the standard  $UBVR_CI_C$  system. The search for variable stars was performed with the TATRY code using the multi-harmonic periodogram of Schwarzenberg-Czerny (1996). Periodograms were calculated for periods ranging from 0.01 day to the time span of a given data set. A total of 21 variable stars were detected. In Table 2 we provide the positional data sufficient for their unambiguous identification.

### 2.1 M13 Variables

Globular cluster M13=NGC 6205 was monitored by the HST/WFPC2 for a period spanning approximately 7 hours. Fig. 1 displays the *rms* deviation as a function of average magnitude in  $I_C$  and  $V$  bands for the light curves of 23374 and 21250 stars, respectively.

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\*<http://archive.stsci.edu>

Table 2: Equatorial coordinates and  $(X,Y)$  positions of variables on the HST/WFPC2 images

Name	RA(2000.0)	Dec(2000.0)	Chip	Location ( $X,Y$ )	Dataset name
M13_01	16 <sup>h</sup> 41 <sup>m</sup> 41 <sup>s</sup> 35	36°27′04″.6	WF2	(119,163)	u5bt0104r
M13_02	16 <sup>h</sup> 41 <sup>m</sup> 38 <sup>s</sup> 77	36°26′20″.9	WF3	(505,401)	u5bt0104r
M13_03	16 <sup>h</sup> 41 <sup>m</sup> 42 <sup>s</sup> 89	36°27′00″.3	WF2	(287,259)	u5bt0104r
M13_04	16 <sup>h</sup> 41 <sup>m</sup> 42 <sup>s</sup> 96	36°27′27″.3	PC1	(104,758)	u5bt0104r
NGC6712_01	18 <sup>h</sup> 53 <sup>m</sup> 04 <sup>s</sup> 83	-8°42′20″.9	PC1	(422,434)	u2of0101t
NGC6712_02	18 <sup>h</sup> 53 <sup>m</sup> 04 <sup>s</sup> 12	-8°42′04″.2	PC1	( 54,671)	u2of0101t
NGC6712_03	18 <sup>h</sup> 53 <sup>m</sup> 05 <sup>s</sup> 98	-8°41′33″.9	WF2	( 53,325)	u2of0101t
NGC6712_04	18 <sup>h</sup> 53 <sup>m</sup> 03 <sup>s</sup> 18	-8°41′39″.7	WF2	(471,269)	u2of0101t
NGC6712_05	18 <sup>h</sup> 53 <sup>m</sup> 04 <sup>s</sup> 33	-8°42′27″.3	PC1	(565,598)	u2of0101t
NGC6712_06	18 <sup>h</sup> 53 <sup>m</sup> 06 <sup>s</sup> 80	-8°41′31″.7	WF3	(355,165)	u2of0101t
NGC6712_07	18 <sup>h</sup> 53 <sup>m</sup> 08 <sup>s</sup> 83	-8°42′31″.3	WF4	(468,320)	u2of0101t
NGC6712_08	18 <sup>h</sup> 53 <sup>m</sup> 08 <sup>s</sup> 07	-8°40′52″.0	WF3	(756,353)	u2of0101t
NGC6712_09	18 <sup>h</sup> 53 <sup>m</sup> 04 <sup>s</sup> 10	-8°42′25″.5	PC1	(526,672)	u2of0101t
M30_01	21 <sup>h</sup> 40 <sup>m</sup> 24 <sup>s</sup> 25	-23°11′47″.1	WF4	(401,590)	u5fw0106r
M30_02	21 <sup>h</sup> 40 <sup>m</sup> 21 <sup>s</sup> 80	-23°10′50″.8	PC1	(500,530)	u5fw0101r
M30_03	21 <sup>h</sup> 40 <sup>m</sup> 22 <sup>s</sup> 14	-23°10′44″.3	PC1	(325,511)	u5fw0101r
M30_04	21 <sup>h</sup> 40 <sup>m</sup> 22 <sup>s</sup> 02	-23°10′46″.7	PC1	(388,515)	u5fw0101r
M30_05	21 <sup>h</sup> 40 <sup>m</sup> 22 <sup>s</sup> 21	-23°10′48″.3	PC1	(392,448)	u5fw0101r
M30_06	21 <sup>h</sup> 40 <sup>m</sup> 22 <sup>s</sup> 51	-23°10′54″.4	PC1	(465,303)	u5fw0101r
M30_07	21 <sup>h</sup> 40 <sup>m</sup> 23 <sup>s</sup> 28	-23°10′40″.6	PC1	( 85,247)	u5fw0101r
M30_08	21 <sup>h</sup> 40 <sup>m</sup> 22 <sup>s</sup> 51	-23°10′50″.9	PC1	(397,342)	u5fw0101r

Table 3: Photometric data for the M13 variables

Name	$V_{max}$	$\Delta V$	$I_{C,max}$	$\Delta I_C$	$P$ [d]	Type
M13_01	17.12	0.18	16.71	0.11	0.0535(4)	SX
M13_02	17.01	0.20	16.58	0.22	0.0644(5)	SX
M13_03	19.96	0.44	19.12	0.48	0.223(1)	EW
M13_04	19.15	0.19	18.39	0.18	-	EA

The most recent list of variable stars from the central region of M13 was published by Kopacki *et al.* (2003). Among a total of 26 variables in that list 13 turn out to be located in the investigated WFPC2 area. However, due to severe saturation of their images no useful photometry could be extracted for any of these stars. Our search for variability led to detection of four new variables. Fig. 2 shows their  $I_C$  and  $V$  light curves while Fig. 3 displays their location on the  $V/V - I$  color-magnitude diagram. Table 3 lists basic photometric data for new variables. Objects M13\_01 and M13\_02 can be securely classified as SX Phe stars. Both of them belong to the population of cluster blue stragglers what is a rule for SX Phe observed in globular clusters. The light curve and period of M13\_03 indicates that it is a W UMa-type contact binary. The variable is located slightly above the main-sequence of its parent cluster what is consistent with its binary nature. Star M13\_04 exhibited an eclipse-like event at the end of observations. The drop of luminosity amounted to about 0.2 mag in both employed filters. Preliminary classification of the object as an eclipsing detached binary is consistent with its location above the cluster main-sequence in the color-magnitude diagram.

The region marked with a quadrangle in Fig. 3 includes 27 candidates blue stragglers. Light curves of these stars were examined individually. None of them, besides two already discussed objects, showed any evidence for a short period variability with an amplitude exceeding 0.02 mag.

## 2.2 NGC 6712 Variables

The HST was pointed continuously at the globular cluster NGC 6712 (C 1850-087) for a period of 13.5 h on 1995 May 25–26. Some gaps in the data occurred during Earth occultations and during South Atlantic Anomaly passages. Time-series observations consisting of 53 exposures were collected in the wide-band F300W filter. Additional exposures in F336W, F439W, F555W, F675W and F814W filters were taken over a period of 20 min on 1995 May 28. The quality of photometry derived for the F300W filter is illustrated in Fig. 4, where we show the *rms* of light curves *vs.* the average magnitude for a total of 4413 of analyzed stars.

Nine periodic variables were detected. Table 4 lists some of their basic photometric characteristics based on observations in the F300W filter. Phased light curves are presented in Fig. 5. The color-magnitude diagrams of the cluster with marked positions of variables are shown in Fig. 6. The adopted colors are based on pairs of frames separated by no more than 6

Table 4: Photometric data for the NGC 6712 variables

Name	F300W <sub>max</sub>	F300W <sub>min</sub>	$P$ [d]	Type
NGC6712_01	19.46	19.65	0.01429(3)	LMXB
NGC6712_02	17.78	18.26	0.249(3)	RRc
NGC6712_03	17.76	18.60	0.502776	RRab
NGC6712_04	17.50	18.01	0.423900	RRc
NGC6712_05	17.61	18.39	0.58(6)	RRab
NGC6712_06	17.58	17.75	0.247(3)	RRc
NGC6712_07	18.62	19.05	0.211(3)	RRc
NGC6712_08	20.12	20.66	0.302(5)	EW
NGC6712_09	21.16	21.88	0.306(10)	EW

minutes. Note also that magnitudes and colors plotted in Fig. 6 were measured at some random phases of variables.

Object #1 is a well known optical counterpart of the low mass X-ray binary X1850-087 (Homer *et al.* 1996). Our objects #2, #3 and #4 correspond to variables V20, V12 and V19 from Clement *et al.* (2001), respectively. We provide a revised value of period for the variable V20. Using the HST photometry we derived  $P = 0.249 \pm 0.003$  d. The period of 0.330870 d listed in Clement *et al.* (2001) does not fit the HST data. Moreover, reanalysis of photometry published by Sandage, Smith & Norton (1966) allows to refine the period of V20 to  $P = 0.248489 \pm 0.000002$  d. Variability of RR Lyr star #5 has been recently reported by Tuairisg *et al.* (2003). Our photometry confirms the period derived by that group for the variable. Stars #6–9 are new identifications. Objects #6 and #7 belong to RR Lyr variables of RRc subtype. We note that star #7 exhibits unstable light curve with some cycle-to-cycle changes visible in obtained photometry. Objects #8 and #9 are preliminarily classified as W UMa-type contact binaries. Such classification is consistent with shape of observed light curves and with location of these variables on the color-magnitude diagram of the cluster. In particular, variable #8 is a candidate for cluster blue straggler.

The region marked with a quadrangle in Fig. 6 includes 39 candidates blue stragglers. Light curves of these stars were examined individually. None of them, besides one already discussed object, showed any evidence for a short period variability with an amplitude exceeding 0.02 mag.

Table 5: Photometric data for the M30 variables

Name	$U_{max}$	$\Delta U$	$V_{max}$	$\Delta V$	$I_{C,max}$	$\Delta I_C$	$P$ [d]	Type
M30_01	14.96	0.92	-	-	-	-	0.751(9)	RRab
M30_02	14.94	1.10	15.21	0.23	14.13	0.66	0.689(8)	RRab
M30_03	15.26	0.52	15.08	0.30	14.54	0.32	0.341(1)	RRc
M30_04	18.01	0.26	17.90	0.27	17.51	0.24	0.284(1)	EW
M30_05	17.39	0.37	17.28	0.28	17.04	0.32	0.3175(12)	EW
M30_06	19.58	0.57	19.54	0.54	18.82	0.52	0.211(1)	EW
M30_07	20.38	0.83	20.06	0.75	19.20	0.73	0.2149(5)	EW
M30_08	19.71	0.43	19.72	0.33	19.20	0.36	0.386(3)	Ell

### 2.3 M30 Variables

The central part of the globular cluster M30=NGC 7099 was observed in three filters for a period spanning 30<sup>h</sup>5. The quality and depth of derived photometry can be inferred from Fig. 7. Light curves for a total of 11096, 10578 and 6833 stars were analysed for filters  $I_C$ ,  $V$  and  $U$ , respectively.

Eight certain periodic variables were detected. Table 5 lists some of their basic photometric characteristics while phased light curves are shown in Fig. 8. The  $U/U - V$  and  $V/V - I$  color-magnitude diagrams of the cluster with positions of variables marked are presented in Fig. 9. It is remarkable that 8 out of 9 variables were detected on the PC1 chip which covers nucleus of the cluster but contains only about 32% of analyzed stars.

Object M30\_01 corresponds to variable V1 from the catalogue of Clement *et al.* (2001). That star could be measured only in the  $U$  band but obtained light curve can be phased with the period listed in Clement *et al.* (2001). The 8 remaining variables are new identifications. The variables #2 and #3 belong to RRab and RRc stars, respectively. Based on observed periods and shape of light curves we have classified stars #4–7 as W UMa-type contact binaries. Such classification is further supported by observed location of these objects on the cluster color-magnitude diagram. Objects #4 and #5 are located among cluster blue stragglers while objects #6 and #7 occupy positions near the red edge of cluster main-sequence.

Object #8 also shows variability with a period falling formally within a range of periods observed for W UMa-type binaries. However, its light curve exhibits too sharp maxima (or alternatively too wide minima) for a contact binary. Also observed location of the variable on the cluster color-magnitude

diagram would be atypical for contact binaries detected so far in globular clusters. The light curve of star #8 exhibits two minima of slightly different depth. One may also note that extrema of the light curve are separated by about  $0.5 P$ . We propose that object #8 is a close binary belonging to ellipsoidal variables although we cannot exclude the possibility that it is an eclipsing binary.

The region marked with a quadrangle in Fig. 9 includes 65 candidates blue stargglers. Light curves of these stars were examined individually. None of them, besides two already discussed objects, showed any evidence for a short period variability with an amplitude exceeding 0.02 mag. We also failed to detect any variables among stars located within  $1''.0$  from the nominal positions of the binary millisecond pulsar M30A recently reported by Ransom *et al.* (2003).

### 3 Conclusions

We have used the archival HST/WFPC2 data to identify 15 new variables located in fields covering central regions of three nearby globular clusters. Among others the sample includes seven W UMa-type compact binaries, one detached eclipsing binary and two SX Phe stars. We do not have any definitive information about membership status of these stars but note that investigated regions are strongly dominated by stars belonging to the respective clusters. Also the location of detected variables on the color-magnitude diagrams favours the hypothesis that most of them are members of investigated clusters. It is possible to obtain more firm conclusions about membership status of detected variables by obtaining second epoch HST/WFPC2 observations and performing suitable proper motion studies (*e.g.*, Anderson *et al.* 2003).

Short time coverage and small number of available images limited sample of detectable variables to objects with period of the order of few hours. In fact, all but one of identified objects show continuous variability which makes their detection far easier than detection of variables with a short duty cycle, such as detached eclipsing binaries. Another factor limiting completeness of derived sample of variables even for objects with short periods is a presence of many bright stars in the investigated fields. Images of these bright stars are severely saturated on the WFPC2 frames. Large number of dead/bad pixels on WFPC2 CCD's is yet another limiting factor.

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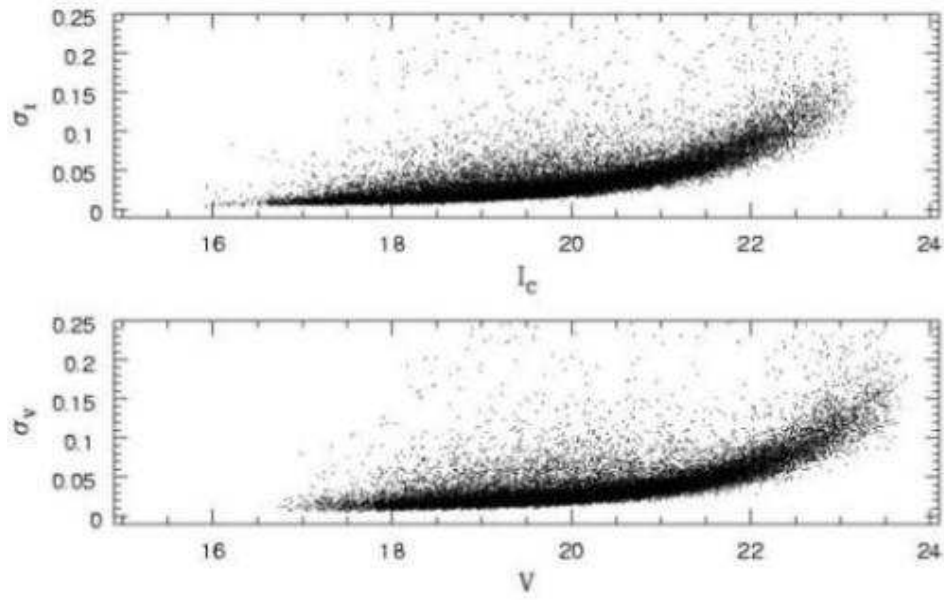


Fig. 1. The *rms* of derived time-series photometry *vs.* the average magnitude for M13 stars.

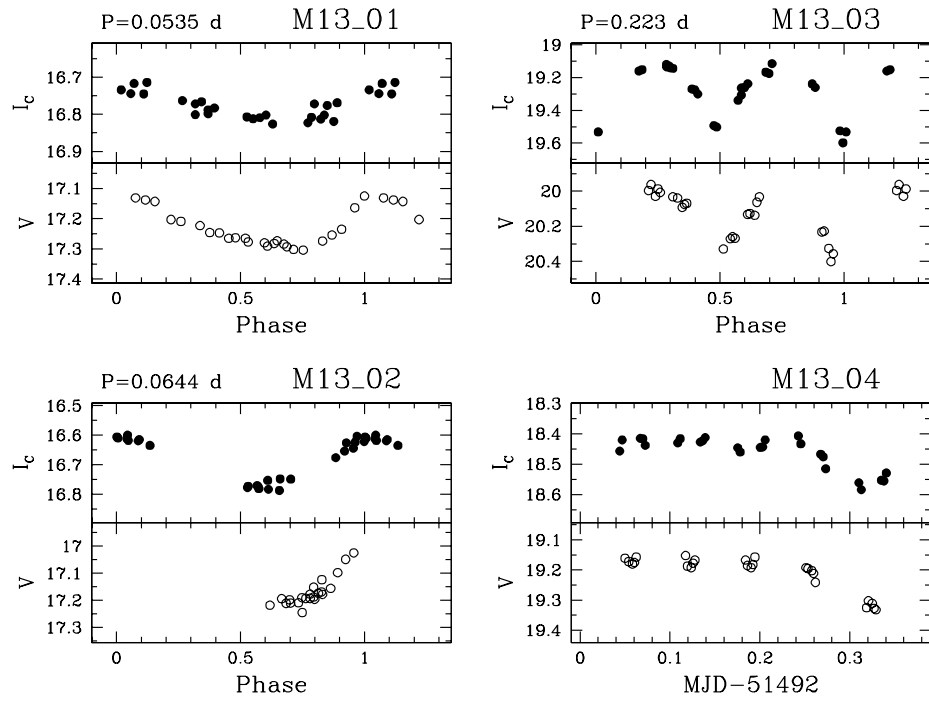


Fig. 2. Light curves for newly detected variables from the field of M13.

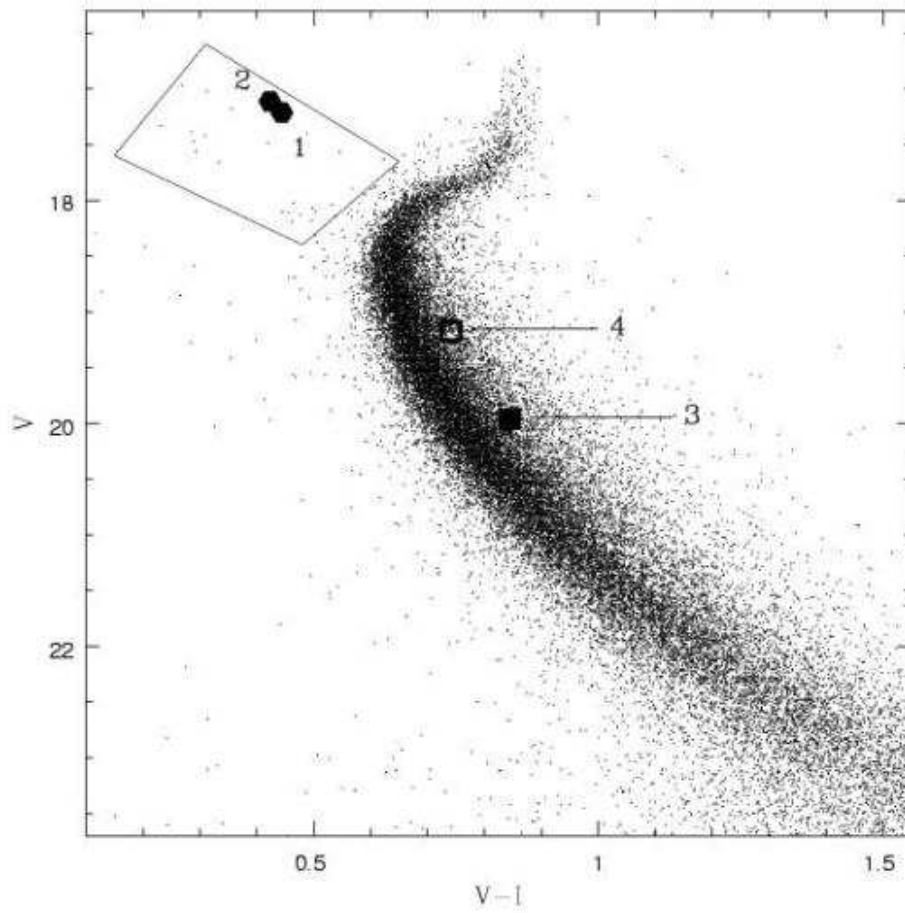


Fig. 3. Color-magnitude diagram of M13 with the positions of detected variables marked.

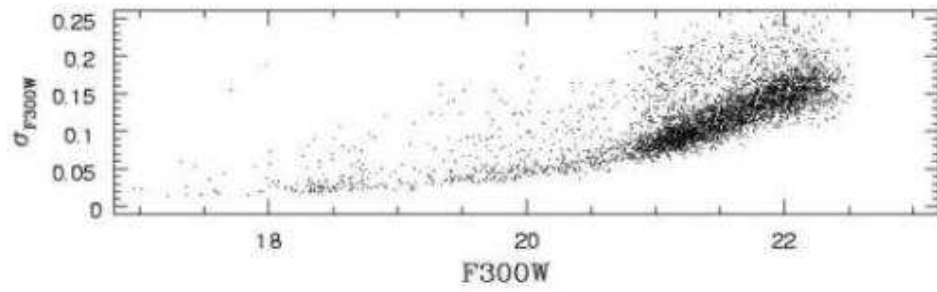


Fig. 4. The *rms* of derived time-series photometry *vs.* the average magnitude for NGC 6712 stars.

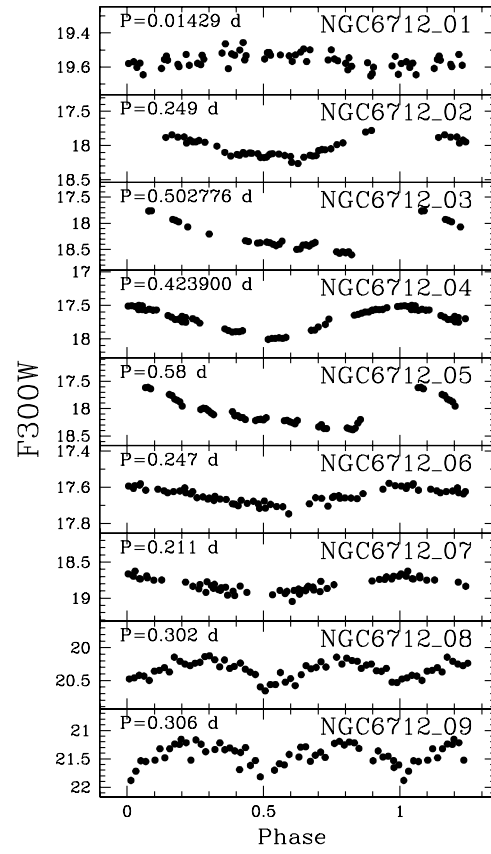


Fig. 5. Phased F300W filter light curves for variables detected in the field of NGC 6712.

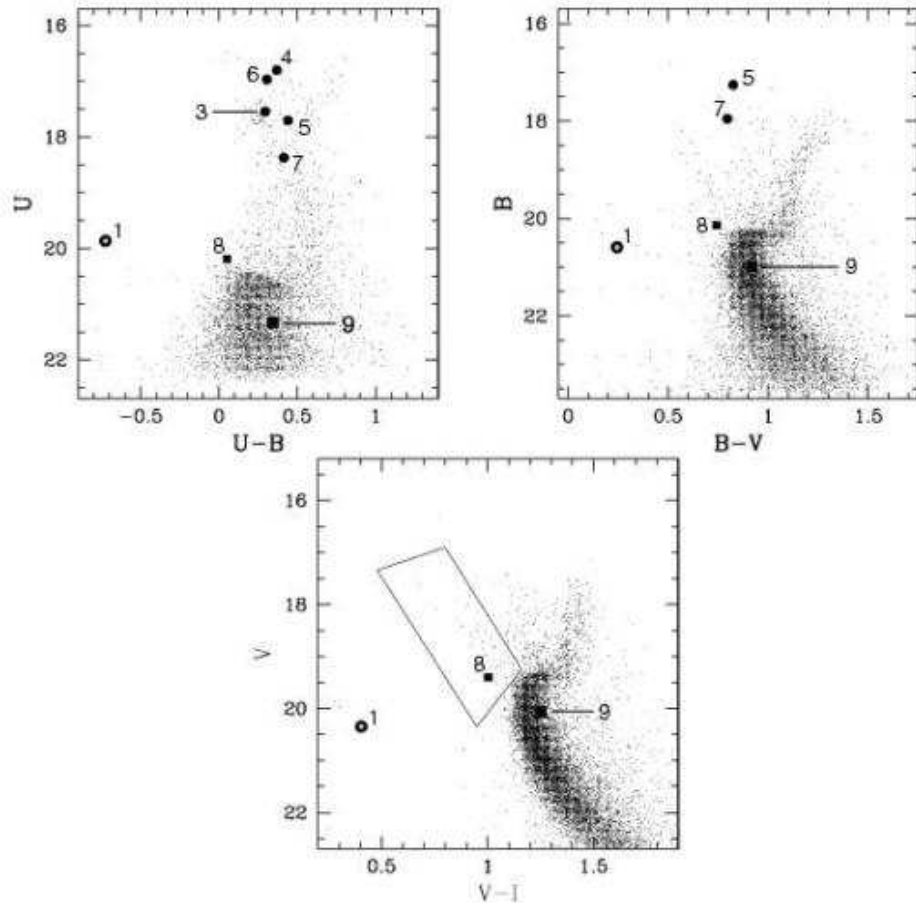


Fig. 6. Location of detected variables in the color-magnitude diagrams of NGC 6712.

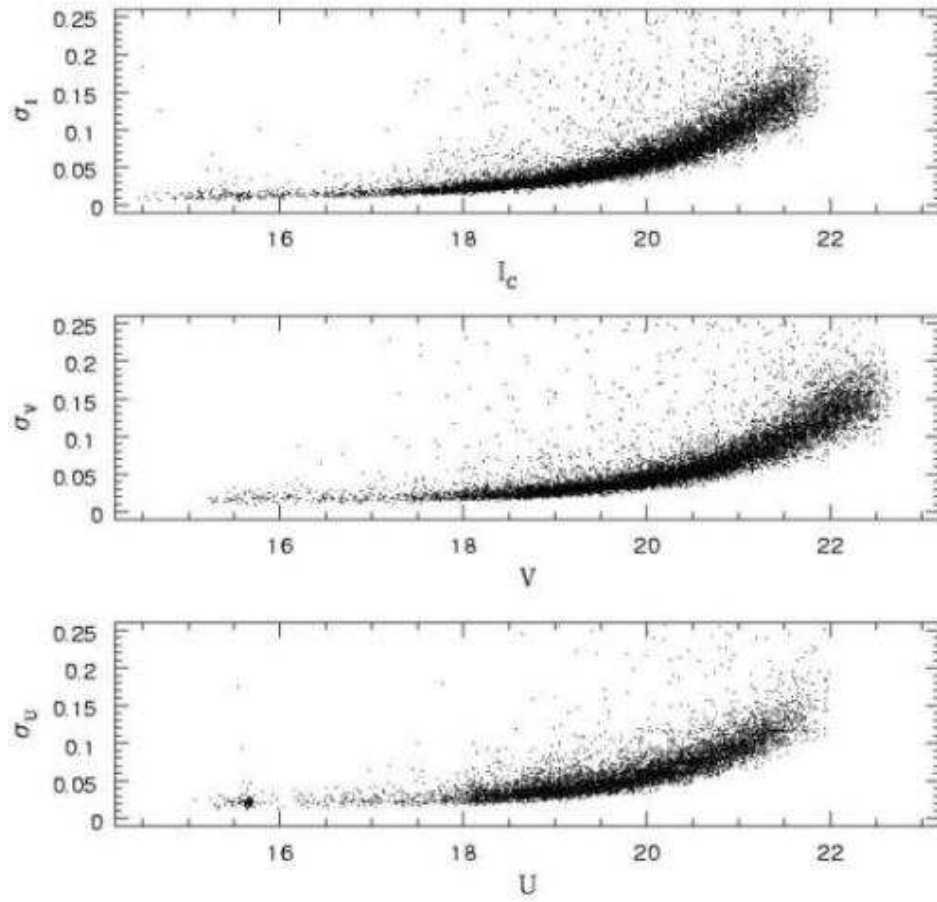


Fig. 7. The *rms* of derived time-series photometry *vs.* the average magnitude for M30 stars.

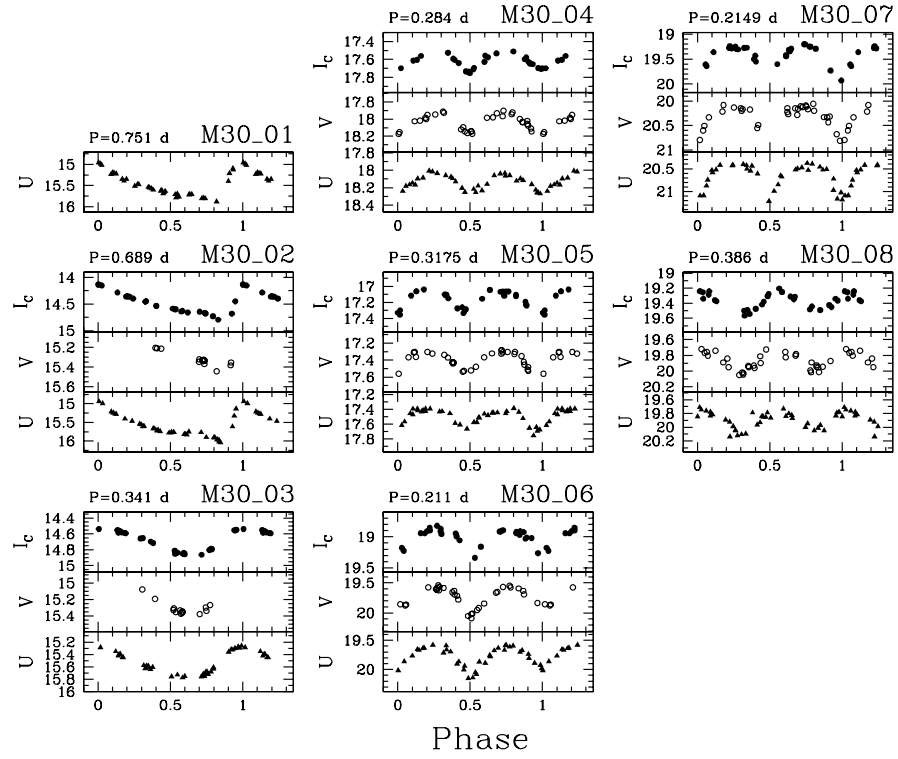


Fig. 8. Phased light curves for variables detected in the field of M30.



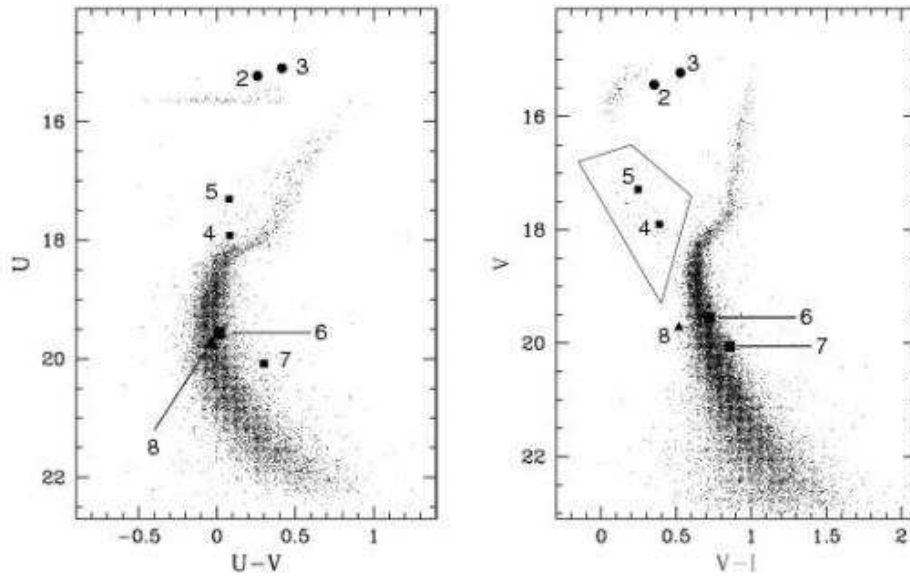


Fig. 9. The color-magnitude diagrams of M30 with location of detected variables marked.